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Mapping suitable sites for water storage structure in the Sokoto-Rima basin of northwest Nigeria

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ABSTRACT

The persistent phenomenon of climate change has resulted in increased dryness and incidence of intermittent drought event as well as advancement of Sahara desert into the Sudano-Sahelian region of northern Nigeria. Part of the effect of this climate variability is increased intensity of rainfall albeit reduction in total amount rainfall, consequently producing high runoff, low infiltration and eventually creating the problem of water scarcity, which has adversely affected crop production, culminating in crop failures and pest infestation in some cases. Adaptation scheme involving rainwater management such as capturing and storing water for future use represents the best possible alternative to the current situation and possibly future scenario.

In this study, sites suitable for location of water storage structures were delineated in the Sokoto-Rima basin by combining eight factors considered important in suitability analysis for water storage structures. The factors considered are land use/cover, soil, geology, slope, drainage density, lineament density, distance to drainage and precipitation. The factors were classified with each class assigned preference value based on insights from previous studies and knowledge of the study area. The factors were integrated through weighted overlay analysis using factors' weights computed from Analytical Hierarchy Process. The result of the suitability analysis showed that 3% (131.89 km^2) area of Sokoto-Rima basin is considered to be highly suitable, 9% (486.19 km^2) of the basin area is moderately suitable, 11% (596.05 km^2) of the basin area have low stability for siting water storage structures while 77% (3967.62 km^2) of the basin is not suitable. Further combination of suitability layer, drainage network, cross-section graph generated from digital elevation model and triangulated Irregular Network (TIN) enable selection of six potential sites for which parameters such as base elevation, outlet elevation, surface area, storage capacity and flood extent were computed.

1. Introduction

Changing pattern of precipitation emerging around the world indicate that climate change is already a reality (Dore, 2005). Increased heating causes higher evaporation, hence more surface drying, which increases duration and intensity of drought (Kevin, 2005). The water-holding capacity of air however increases by approximately 7% per 1 °C warming, which causes increased water vapor in the atmosphere, and this provides the greatest influence on precipitation. Any disturbed state of the atmosphere, especially as affecting the earth's surface, supplied by increased moisture, produce more intense precipitation events which are now common occurrence, even in regions where total precipitation is decreasing. This has lead to increases flood risk. This changing rainfall pattern have been in many areas, with increased dryness in dry areas (generally throughout the subtropics) and wet areas becoming wetter, particularly in mid to high latitudes (Kevin, 2005).

In Nigeria, climate change is having an abundance of direct and indirect impacts on water resources. These include drought, desertification drying up of water bodies and flash flood in the northern part of the country, while the southern part have been battling the problem of sea level rises, salt water intrusion, flooded terrain resulting poor water quality in surface and the subsurface (Akujieze et al., 2003; Bello, 1998; Danladi et al., 2017). Compounded climatic effects have drastically affected the ecosystems and communities, ranging from social and economic impacts to food insecurity and health challenges, evidence of which can be found in North Nigeria (Urama and Ozor, 2010).

The Sudano-Sahelian region of Nigeria have a continuous history of increasing dryness and have experienced increased incidence of drought accentuated by climate change (James, 1973; Mortimore, 1973; Ola-Adams &and Okali, 2006; Olofin, 1985). The situation in the Sudano-Sahelian region of Nigeria is that of a steady advancement of the Sahara desert and increasing desertification making large expanse

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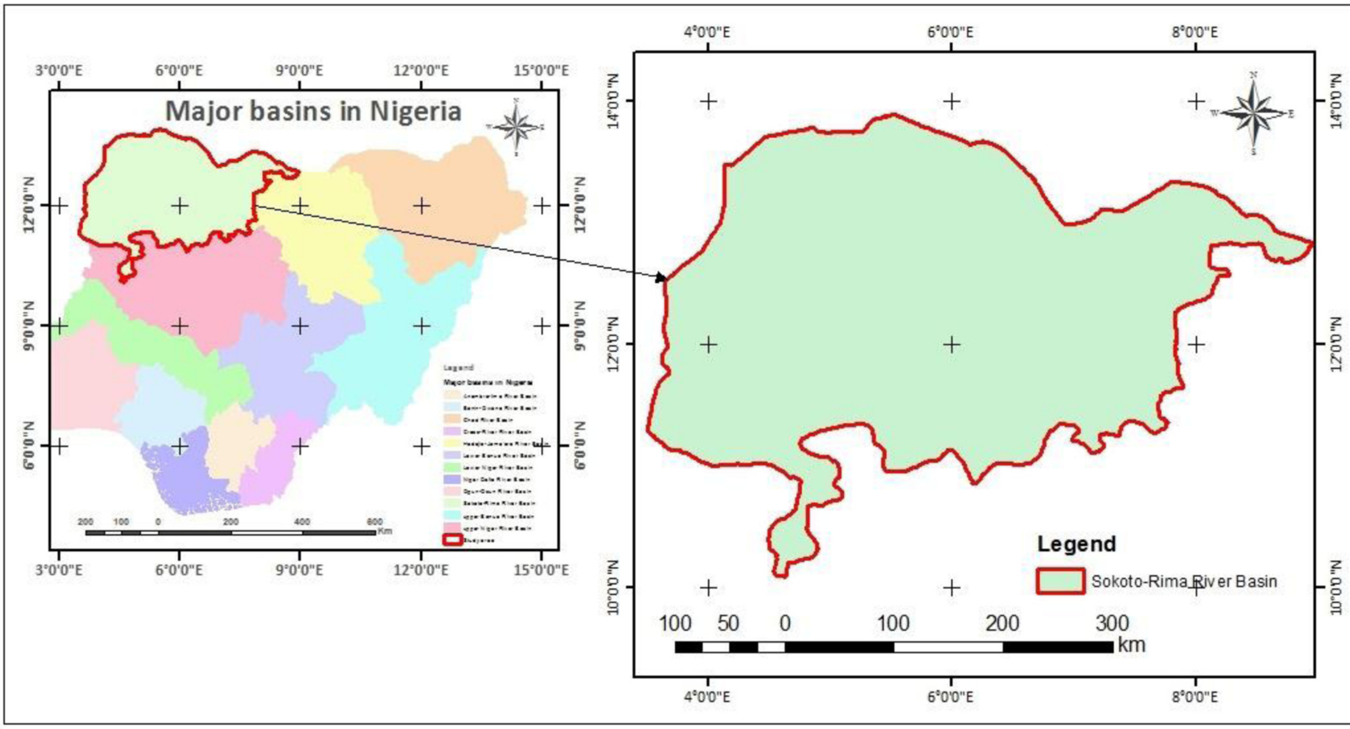

Fig. 1. Major river basins in Nigeria and location of study area.

Table 1
Information and sources of data used in this study.

Data	Details of data	Format	Extracted layer	Generated layer	Data type
RS imagery[a]	Landsat8 2017	TIFF	Land use/Land cover	Land use/Land cover	Raster
			Lineament	Density	Raster
Geological map[b]	1:100,000	Hardcopy	Lithology	Lithology	Vector
Soil map[c]	1:500,000	Hardcopy	Soil	Soil types	Vector
Precipitation data[d]	GCM	TIFF	Ave. Precipitation	Rainfall distribution	Raster
SRTM DEM[e]	DEM	TIFF	Slope	Slope	Raster
			Drainage network	Drainage order	Raster
				Drainage density	Raster

[a] Remotely sensing imagery downloaded free from Landsat on AWS (http://landsatonaws.com).
[b] Geological map obtained from the Nigerian Geological Survey Agency (NGSA).
[c] Soil derived from the Nigerian Geological Survey Agency (NGSA).
[d] Precipitation data obtained from http://worldclipms.com/.
[e] SRTM DEM downloaded from http://dwtkns.com/srtm30m/.

Table 2
Software and their uses for this study.

Software	Functions
ArcGIS 10.5	**Special analysis and data integration**
ENVI 5.0	**Image classification**
PCI Geomatica 2015	**Lineament extraction**
Watershed Modeling System	**Water Storage Structure capacity estimation.**
Gridded Surface Subsurface Hydrologic Analysis model	**Water storage structure break analysis**

of previously viable grazing and arable land become unavailable and unproductive (Ajaero et al., 2015). Occurrences of drought in northern Nigeria has be attributed primarily to the failure of the rain-bearing monsoon winds from the Atlantic Ocean to penetrate sufficiently enough into the region. Desertification on the other, have be linked to a number of factors which include physical condition of soils, disruption

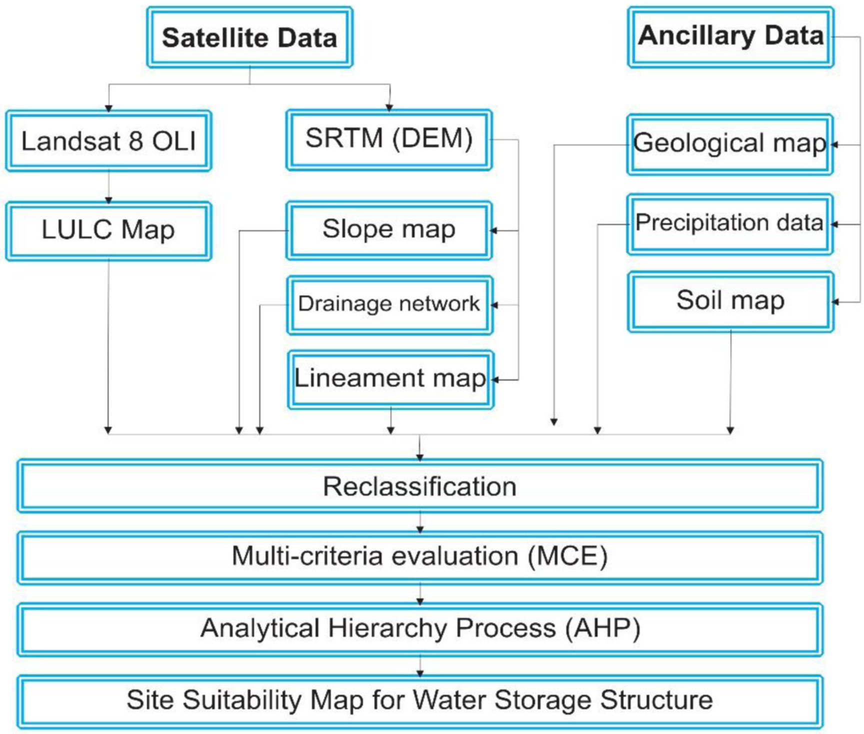

Fig. 2. Flowchart for identifying suitable location of water storage structure.

Table 3
Scale for pairwise comparison (Saaty and Vargas, 1991).

Intensity of importance	Description	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Equal to moderate importance	
3	Moderate importance	Experience and judgement slightly favor one activity over another
4	Moderate to strong importance	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong importance	
7	Very strong importance	An activity is favored very strongly over another it is documented in practice
8	Very strong to extremely strong importance	
9	Extremely strong importance	The evidence favoring one activity over another is of the highest possible order to affirmation
Reciprocal of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j. The j has the reciprocal vale when compared with i	

Table 4
Unified preference value for land use/cover types.

Land use/cover	Preference value	Unified preference
Water Body	1	50
Built-up	0	0
Rock outcrop	0	0
Farmland	2	95

of ecological system caused by poor land use, vegetation, topography, intrinsic climatic vagaries, and continuous increase in demand being made upon the available land resources for agricultural needs to meet the growing demand for food (Oladipo, 1993).

Northwestern part of Nigeria has witnessed remarkable expansion, growth and developmental activities such as buildings, road constructions, farming, and deforestation along with other anthropogenic activities associated with tremendous increase in population. This has resulted in increased demand for water for agricultural, industrial and urban needs. Shortage of sufficient water to cater for these needs usually creates the challenge water scarcity particularly during the dry season. Unavailability of water for consumption and agricultural purpose usually lead to outbreak and spread of diseases and food shortage such as diarrhea and cholera leading to the degeneration quality of life in the region.

Access to safe water supply within Sokoto-Rima basin has great influence on the health, economic productivity and quality of life of the

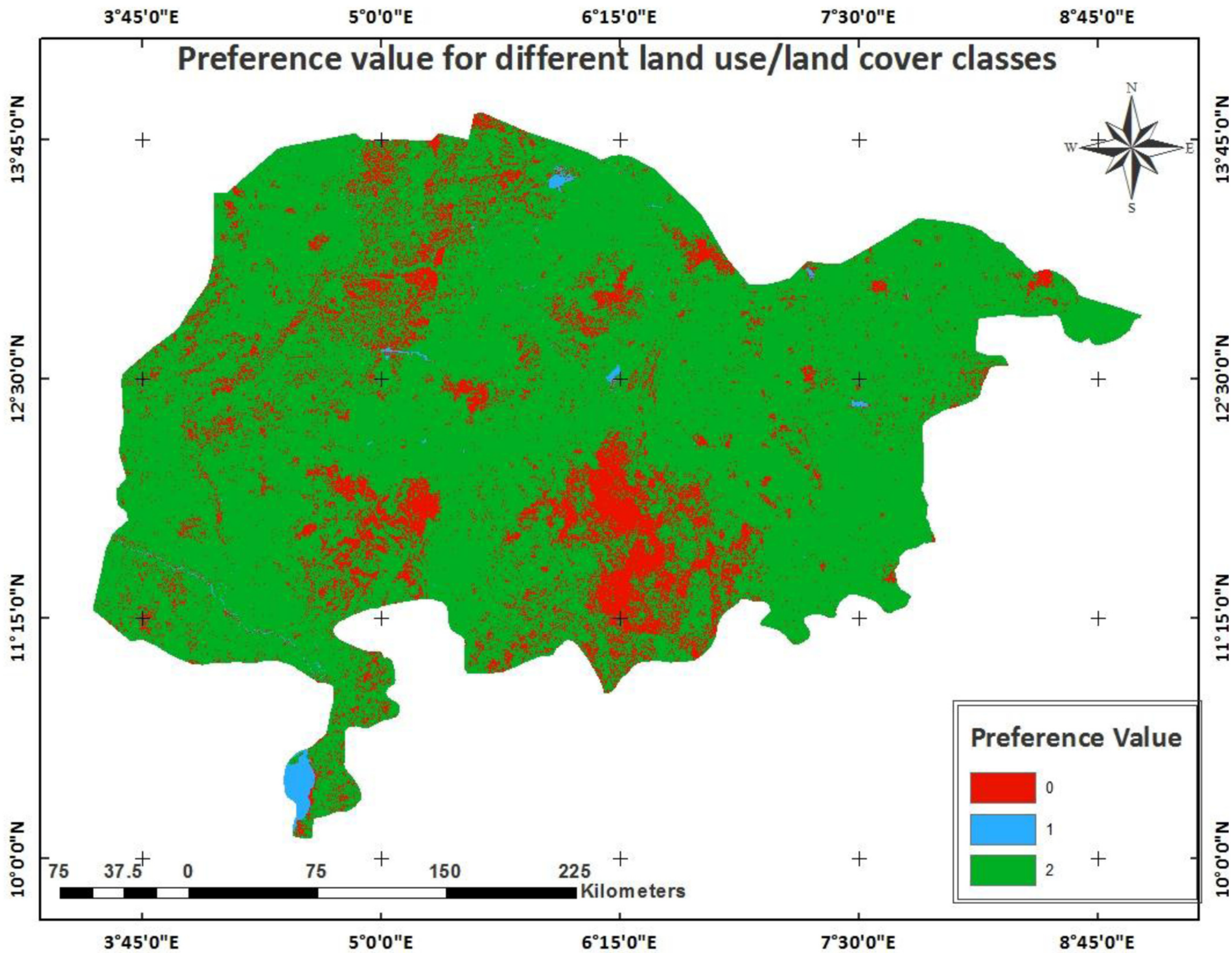

Fig. 3. Reclassified land use/cover of the study area.

people. Meeting this need is the major problem facing the community. Over 70% of households in the community do not have access to improved water supply (Salih and Al-Tarif, 2012). They solely rely on free source such as rain, perennial streams, ponds and unprotected wells, which makes them vulnerable to water borne diseases such as typhoid fever, cholera and dysentery. With the larger proportion of the populations engaged in farming, settlement are general small and are scattered over large area, making pipe borne water supply difficult (Ishaku et al., 2011). Interventions by the government to alleviate the challenge of water scarcity involve the provision of wells and boreholes. Unfortunately, exploration for groundwater is quite challenging in this area. The rugged topography and high relief constitute a major hydrogeological challenge resulting in high rate of well failure, while some of productive wells yield no or little water during the dry season which would not support the population, leading to water crisis and shortages (Akujieze et al., 2003). This situation alters farming and forces households especially the women and children to spend more time walking longer distances during the dry season to trot water for domestic purposes. The inability of current water supply scheme meet the increasing demand necessitates the consideration of innovative alternatives with short and long term benefits. It is paramount to explore prospects of adapting current and increasing vagaries in. Rainwater harvesting using storage structures represents one of the readily adaptable solutions, as small-scale reservoirs have been found to play significant roles in adaption to climate variability, while increasing household income in sub-Saharan Africa rainfall (Cofie and Amede, 2015).

1.1. The study area

The study area for this study is the Sokoto-Rima River basin (Fig. 1) with a total area of 126,174 km^2. It covers four states in the north-western Nigeria and thus lies within the semi-arid region or Sudano-Sahelian region which according to IPCC (2007) is highly vulnerable to climate change. The area is mainly covered with light forest, grass land, and stunted trees. The climate is dominantly controlled by two air masses which determine the two dominant seasons, which are the dry and wet season. The air masses are Tropical Maritime and Tropical Continental, blowing from the Atlantic and the Sahara Desert respectively. The area experiences a prolonged dry season often dominated by dusty harmattan winds from October to April. The greatest food insecurity concerns exist in extreme northern Nigeria which include the Sokoto-Rima River basin. According to United States Agency for International Development (USIAD) (2012), the region is amongst the areas classified as “stressed” under the 2012 estimated food security conditions in Nigeria and will have serious implications in the near

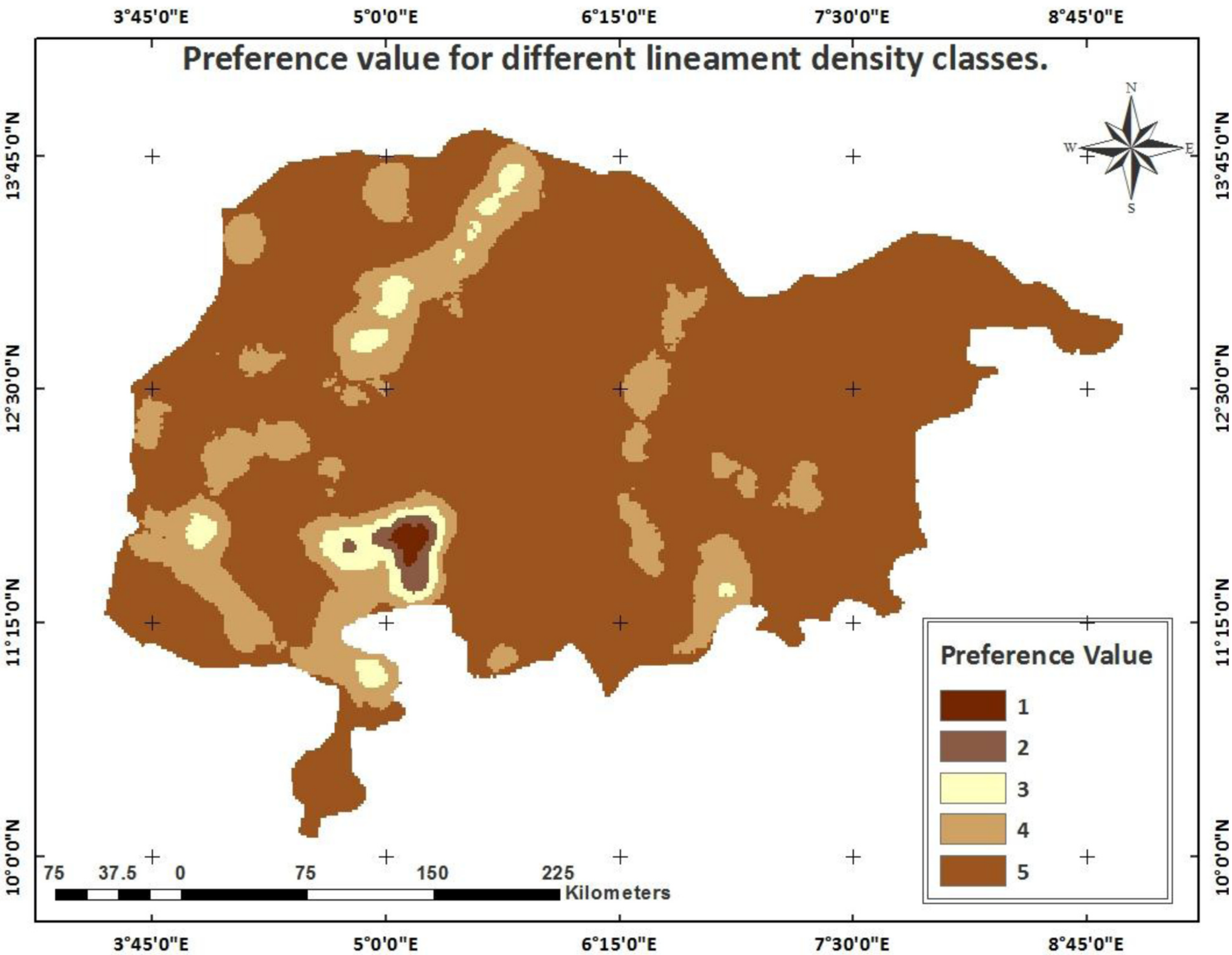

Fig. 4. Reclassified lineament density preference map.

Table 5
Preference value for the lineament density classes.

Lineament density (km^2)	Preference value	Unified preference
0–0.000179	5	95
0.000179–0.000358	4	75
0.000358–0.000537	3	50
0.000537–0.000716	2	25
0.000716–0.000895	1	0

future. Relative humidity is largely low (40%) for the major part of the year with the exception of the wet season when it rises to an average of 80%. This underlying reason for the hot and dry weather experienced in the northern region, which is in sharp contrast to a hot and humid weather experienced in the southern parts of Nigeria (Kowal and Knabe, 1972). The study area extends between latitudes 10°N and 14° N and longitudes 3°E and 9°E. The drainage system is dominated by River Rima system with major tributaries like Gawon, Zarnfara and Gubinka. These tributaries rise in the Basement Complex region of Sokoto State and flow westward to join the River Rima. However, in the southern part of the basin, there are other less important rivers such as Danzaki, Soda and Kasanu, all of which flow to join the River Rima (Ojo, 2014). Sokoto Rima basin can be categorized into three morphological units, viz. the uplands dominated by dissected crystalline rocks with hill ranges and domical rises (inselbergs) occurring in the south and southeast, the plains occurring in the north and centre, and the riverine lowland of the Niger and lower Rima valleys occurring in the west (Swindell, 1986).

Agriculture through irrigation is widely practiced and crops cultivated include grains, cotton, groundnuts, tuber crops and sugar cane. Water is crucial to advancement of sustainable agricultural in this kind of region, as it directly affects several aspects of sustainability such as economic, health, environmental and social aspects (WWAP, 2015). The increasing demand in food necessitates implementation and intensification of sustainable of agriculture programmes, which hinges greatly on the availability of water. Rainwater harvesting and storage structures such as ponds, dams and small reservoirs might therefore offer some of the water required to drive sustainable agriculture in the Sokoto-Rima basin. Additionally, these structures can be used to mitigate the occurrence of flash floods (Saher et al., 2013) associated with short but high intensity rainfall which characteristic in the Sokoto-Rima basin by controlling the amount of water flowing downstream after heavy rain (Ola-Adams and Okali, 2006), and at the same increase

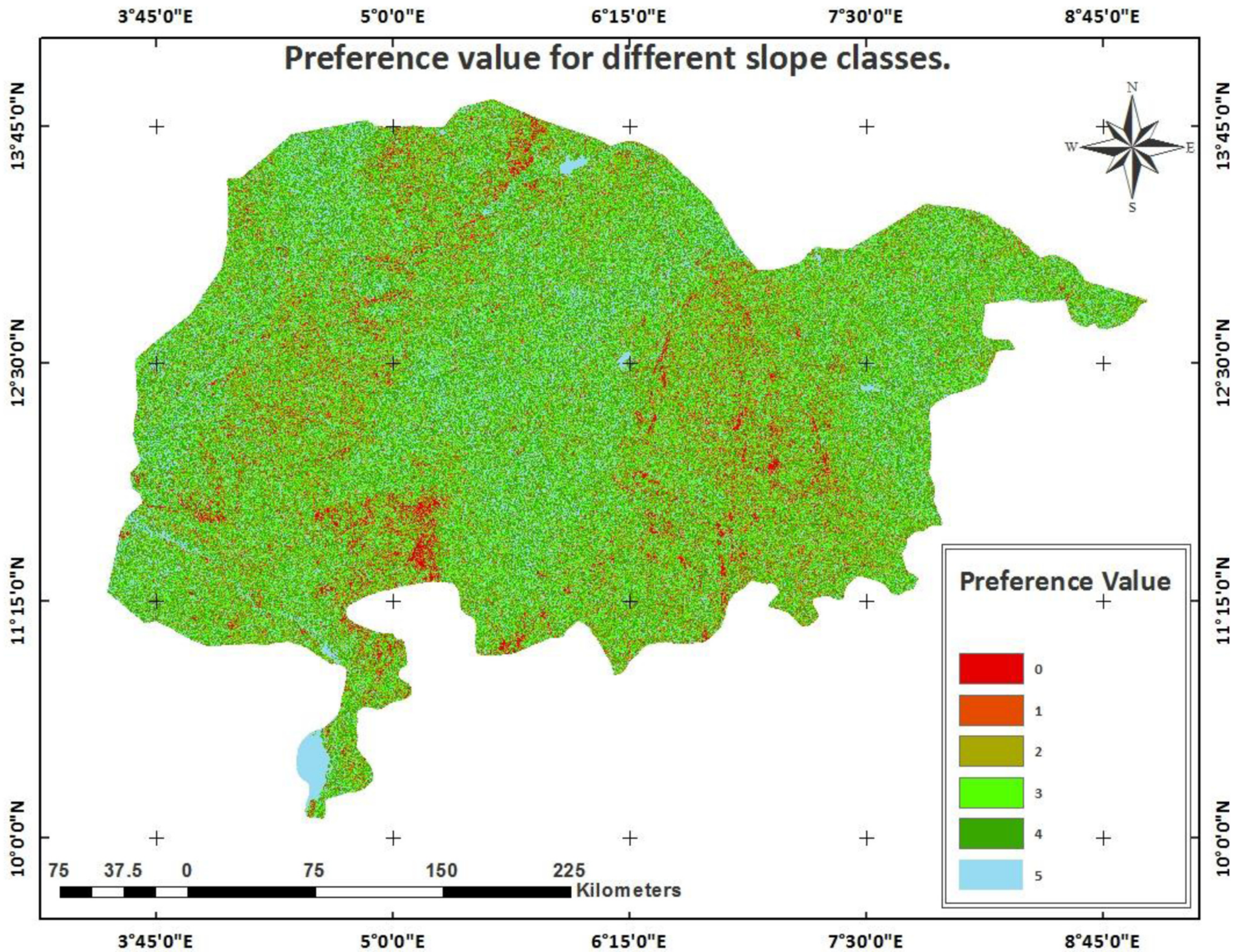

Fig. 5. Map showing the spatial distribution of the preferential slope classes.

Table 6
Preference value for different slope classes in the study area.

Slope (degree)	Preference value	Unified preference
0–1	5	95
1.001–2	4	80
2.001–3	3	60
3.001–4	2	40
4.001–5	1	20
5.001–72.609	0	0

Table 7
Precipitation classes and their preferential values.

Predicted precipitation (mm)	Preference value	Unified preference
39.167–50.983	1	20
50.983–62.800	2	40
62.800–74.617	3	60
74.617–86.433	4	80
86.433–98.25	5	95

groundwater recharge due to retention of water for longer periods.

2. Materials and methods

Based on the review of several literatures relating to this study, specific conditions of Sokoto-Rima basin area and data available, 8 criteria were weighted as main factors for this study. These factors include: Land use/cover type, resistance of geological layer, soil type, amount of predicted precipitation, Slope, lineament density and level of drainage network.

2.1. Factors influences suitability site of water storage structure

Consideration of Land use/cover information is important in the siting of water storage structures. How people utilize land and physical material at the surface of the earth influence the location of water storage structures. Resistance of geological layer is a factor the influences the safety of water storage structures and it is influenced by the rock types in the area. Soil types and their characteristics is also major factor to consider in site suitability evaluation for water storage structures. Soil characteristics such as: surface structure affects the amount

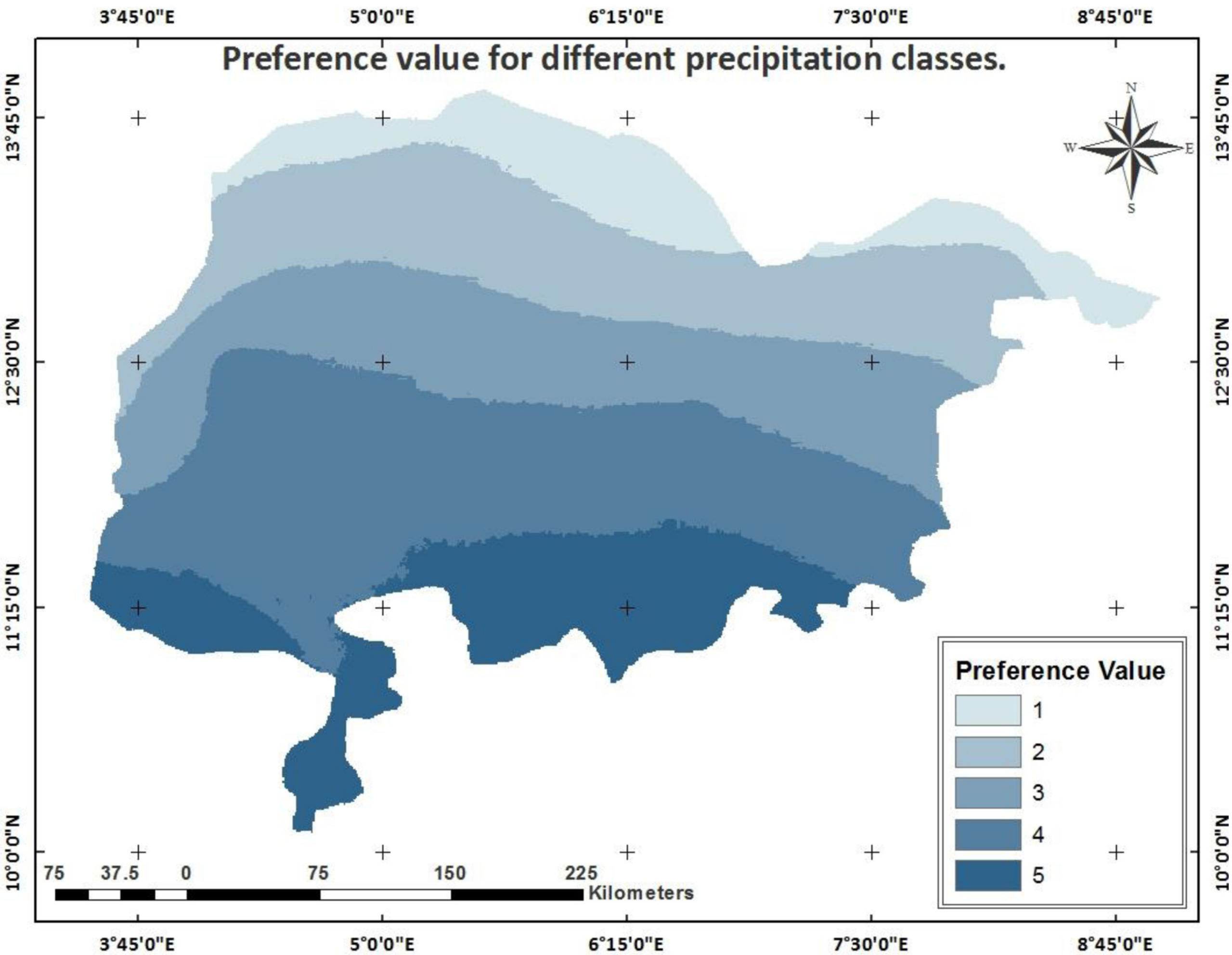

Fig. 6. Preference values for different precipitation classes.

Table 8
Preference value for the soil types in the study area.

Soil type	Preference value	Unified preference
Sand	1	20
Loamy sand	2	40
Sandy loam	3	60
Loam	4	80
Sand clay loam	5	95

of the runoff generated, infiltration rate and invariably determine water movement into the soil. Soil texture and depth also affects the amount runoff and the amount of water stored in the soil (Prinz and Singh, 2000). The knowledge of rainfall characteristics (intensity and distribution) and climate of the study area was considered important in identifying suitable areas for water storage structures. The available rainfall and climatic data series in space and time in the past was used to predict the amount of precipitation and understanding the rainfall runoff process. Slope which is also a major factor influences both runoff and slope stability. Since higher degree of slope has a higher risk of landslides and exert more pressure on foundation of the structure which might eventually leads to structural damage. Lineaments such as circular anomalies, escarpment, fault, fold, fracture and trend line reflect some subsurface phenomenon of possible zone of weakness, thus water storage structures are sited in areas with low lineament density. Drainage network provides necessary runoff water for required for storage in the structure. Different levels of drainage network indicates different amount of runoff. The low other streams discharge or feed high order streams, thus high order streams which are main stream are gathering channels for numerous low order streams are most suitable for locating water storage structures.

2.2. Data collection and processing

To derive the various factors considered in site suitability analysis, the following data were utilized: Shuttle Radar Topographic Mission (SRTM) digital elevation model (DEM) with 30 m spatial resolution (1 arc-second), Landsat 8 OLI data (p188 r051; p189 r051; p189 r052; p190 r051; p190 r052; p190 r053; p191 r051; p191 r052), geological map, soil map and precipitation data. Details of the source of each data type and the factor derive from each data is presented in Table 1.

The coordinate systems of all the data used were unified by projecting to WGS 1984 UTM Zone 31 N. Pre-processing procedures of atmospheric correction, conversion to top of the atmosphere (ToA) reflectance, sun angle correction, mosaicking and layer stacking were

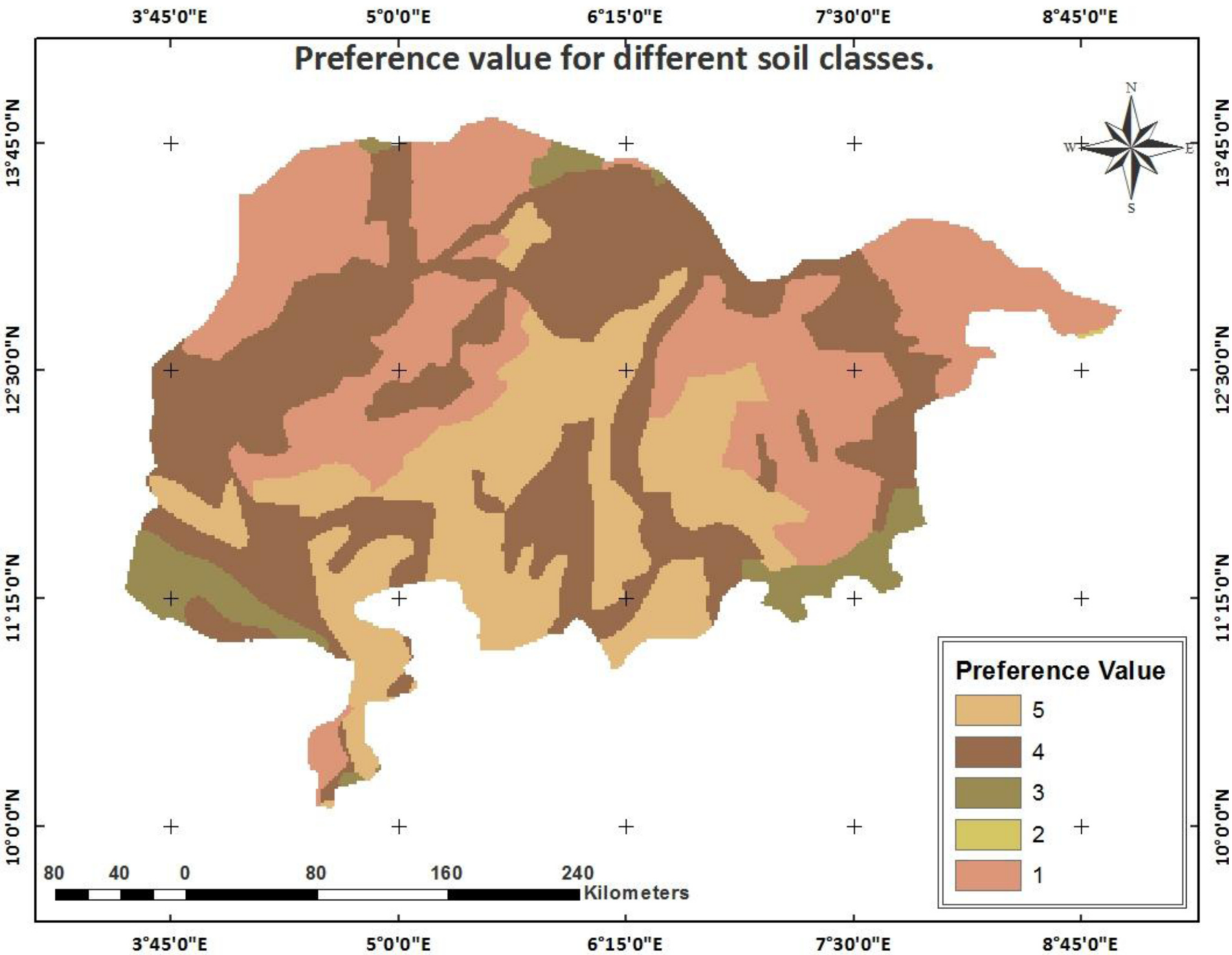

Fig. 7. Map of soil types and assigned preference values.

applied on the Landsat OLI data while sink filling and mosaicking were applied on the DEM. The various software used and the function for which they are employed is presented in Table 2.

The dataset given in Table 1 were used to derive the factors considered while Fig. 2 shows the methodological flowchart of procedures followed in suitability analysis of water storage structure in the study area.

The land use/cover types of the study area were obtained from nine Landsat 8 OLI scenes. The Landsat data were corrected for atmospheric influences and converted to reflectance using FLAASH atmospheric correction in ENVI 5.2 software. The corrected scenes were then merged into one from which land use/cover was derived through supervised classification using the maximum likelihood algorithm in the ENVI 5.2 Software. Lineament includes fractures, faults and folds was identified in the study area.

The DEM (SRTM 30 m resolution) used for lineament extraction, slope computation and extraction of drainage network. For lineament extraction, sobel filter was applied on the DEM using ENVI 5.2 software. Sobel filtering is a discrete differentiation operator, which computes an approximate gradient of the image intensity function. The result of the Sobel–Feldman operator at every point in the image is either the corresponding gradient vector or the norm of this vector. The Sobel–Feldman operator functions by applying small, separable, and integer-valued filter in the horizontal and vertical directions during convolution and is therefore computationally inexpensive. The gradient approximation produced by sobel filtering is relatively crude, in particular for high-frequency variations in the image (Sobel, 2014), thus further analysis is required to identify edges enhanced in the resulting edge image. PCI Geomatica was subsequently for automated identification of edges and lineament extraction from sobel filtered edge image. The extracted lineaments were converted into measurable quantity by computing the density of lineaments using the line density function in ArcGIS. Slope was also computed from the DEM using slope computation algorithm in the surface analyst tool of ArcGIS. The drainage network in the study area were extracted from the DEM using the hydrology tool in ArcGIS. The drainage density was computed following the same procedure using in computation of lineament density. The drainage were also order with the high order stream considered most suitable for construction of water storage structures.

The soil and geological data for Sokoto-Rima basins area were acquired from Nigeria Geological Survey Agency. The maps were scanned and converted to digital format through digitizing. Further processing involves rasterization of the digitized data to convert it to a format suitable for analysis.

2.2.1. *Analytical Hierarchy Process*

The Analytic Hierarchy Process (AHP) is one of the multi-criteria analysis (MCA) is an analysis method that can be used in aiding the decision-making process in a GIS (Mendoza et al., 1999). MCA is considered as a tool utilized in estimating the importance of the different factors involved in a project, and the final decision making process relies on these criteria. MCA's objective is not necessarily aimed to making a final and definite decision, but to help mainly in the process itself (Gül et al., 2006). At one point, this statement admits the

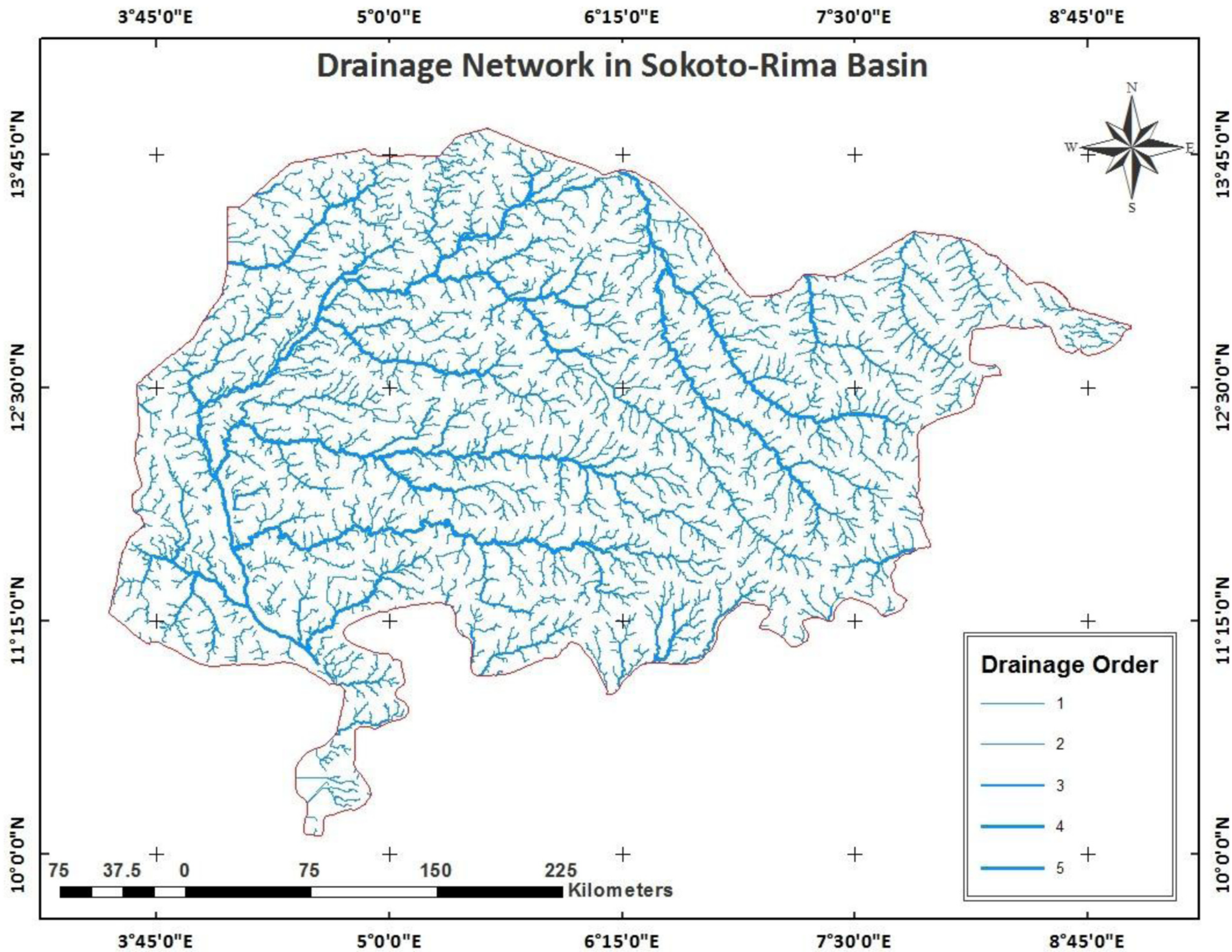

Fig. 8. Drainage order of the study area.

shortcomings of the method. Nevertheless, it is still an important means on how one can arrive to a particular decision. MCA has been used in several suitability analysis and has been found to have high efficiency in finding suitable locations (van der Horst and Gimona, 2005; Gül et al., 2006; Zucca et al., 2008). In addition, MCA is adaptable to large areas and multidisciplinary datasets, and at the same time, it is can easily be implemented. The competency of multi-criteria techniques to essentially associate several factors for proper decision making has increased its use in locating suitable site for water storage structures (Abushandi and Alatawi, 2015; Qureshi, 2010; Salih and Al-Tarif, 2012). Analytical Hierarchy Process (AHP) is one of the most commonly used multi-criteria decision making techniques (Aladejana et al., 2016) due to its versatility and capability to integrate multidisciplinary datasets. AHP relies mainly on the verdict of experts to derive preference value to the factors.

AHP was developed by Thomas L. Saaty in the late 1970s (Saaty, 1980) and has been extensively studied and refined since then. AHP is an intense decision making model as well as one of the most used MCDM method. Using AHP, both tangible and intangible criteria can be measured with absolute scale by using AHP (Saaty, 2013).

The procedure of AHP can be divided into three parts, which include identifying a hierarchy of objectives, criteria and alternatives; pairwise comparison of criteria; an integration with result from pairwise comparison as relative importance over all levels of hierarchy (Saaty, 1988). Saaty and Vargas (1991) suggested a scale for comparison consisting of values ranging from 1 to 9 which describe the intensity of importance (preference/dominance). In this scale, a value of 1 indicates “equal importance” and a value of 9 indicates factors with “extreme importance” over another factor (Saaty, 1977). Table 3 shows the fundamental scale of absolute numbers with brief explanation.

The combination of AHP with GIS results in a well-organized and helpful way for solving complex problems as it is a combination of decision making support method and tools with powerful capabilities of mass data computation, visualization, and mapping (Marinoni, 2004). The implementation of AHP in ArcGIS, which is one of the most used GIS software globally, can be summarized as following established method: definition of objective; identification of criteria; data collection and preprocess; digitization of criteria and convert all data into raster data; classification of raster datasets; creation of preference matrix; determination of criteria weights according to calculation based on preference matrix; weighted summation of criteria raster datasets as result (Marinoni, 2004).

2.2.2. Pairwise comparison of the thematic layers (evaluation criteria)

Pairwise comparison is applied on all criteria using the fundamental scale shown in Table 1 which was suggested as part of AHP by Saaty in 1977. Intensity of importance is assigned to criteria i when compared to criteria j and the reciprocal value is assigned to criteria j as intensity of importance. When comparison between all possible criteria pairs is done, the weight of criteria i, which was later used in analysis for suitability analysis, is calculated using Eq. (2) (Saaty, 1977).

$$w_i = \frac{\sum_{j=1}^{n} P_{ij}}{\sum_{i-1}^{n} \sum_{j=1}^{n} P_{ij}} \quad (1)$$

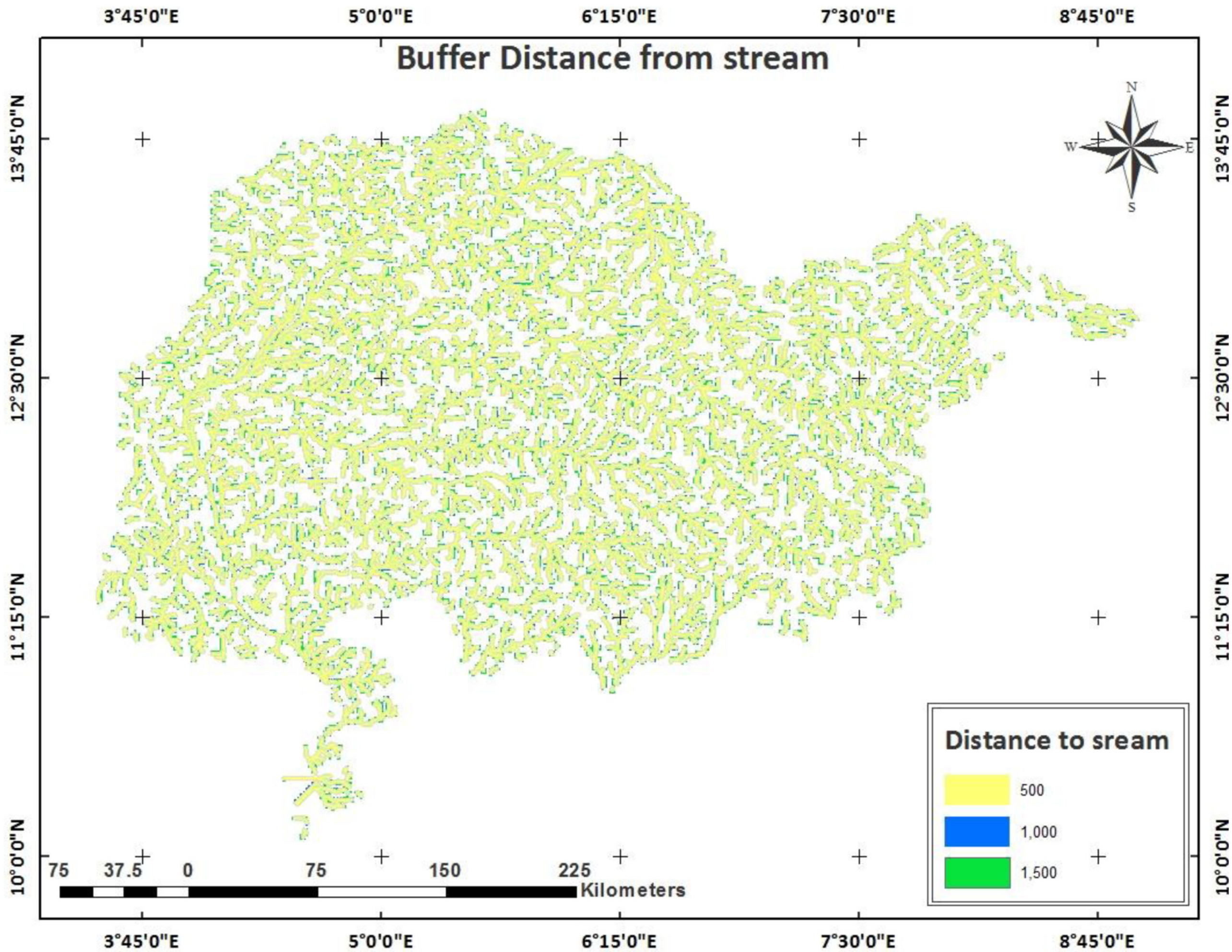

Fig. 9. Map of preference values for specified distances from drainage channels.

Table 9
Preference values for distances to river channels.

Distance to stream (m)	Preference value	Unified preference
500	3	95
1000	2	60
1500	1	30

Table 10
Preference value for the various lineament density classes.

Drainage density (km^2)	Preference value	Unified preference
0–0.000179	1	20
0.000179–0.000358	2	40
0.000358–0.00054	3	60
0.00054–0.000716	4	80
0.000716–0.000895	5	100

in which P_{ij} indicates relative importance in pairwise comparison of criteria i comparing to criteria j.

2.2.3. Weighted index overlay analysis for site suitability

The weighted index overlay analysis is an easy technique for combined analysis of multiclass maps to achieve a particular objective. The major advantage of this technique is that knowledge and experience based human verdict can be incorporated into the assessment. The weights given here signify the relative importance of a factor and the attributes of each factor to the overall objective (Aladejana et al., 2016). Suitability of water storage sites was calculated as weighted summation of different factors using ArcGIS weighted overlay extension tool. In this study, a total of 8 factors derived from satellite imageries and other ancillary data were considered for the siting of water storage structures within Sokoto-Rima basin area. The pixel size of all the thematic layers was set at 30 m resolution

Weight of different factors are shown in Table 4. In other to exclude water bodies, rock outcrops and built-up areas, a Boolean operation was performed on land use/cover layer, which has the class of water and built up area set as value 0 and other classes with value 1. The resulting layer was then reclassified in other to differentiate different levels of suitability of the other classes.

2.2.4. Computing cross section, surface area and storage capacity of proposed water storage structure sites

For every proposed location for top ranked water storage structure, 5-m interval contour layer is generated from DEM and the base height is selected according to elevation of the water storage structure. For drawing interpolation line, which is essential to get cross section profile, and calculating volume of reservoirs, Triangulated Irregular Network (TIN) and 5-m interval contour line layer were used. Hence, possible heights of water storage structures were estimated. The cross section of the proposed location for water storage structures were generated with ArcGIS 3D analyst tool. In order to estimate the capacity of the potential suites for water storage structures, suitable outlet elevations where generated and these elevation varies among different

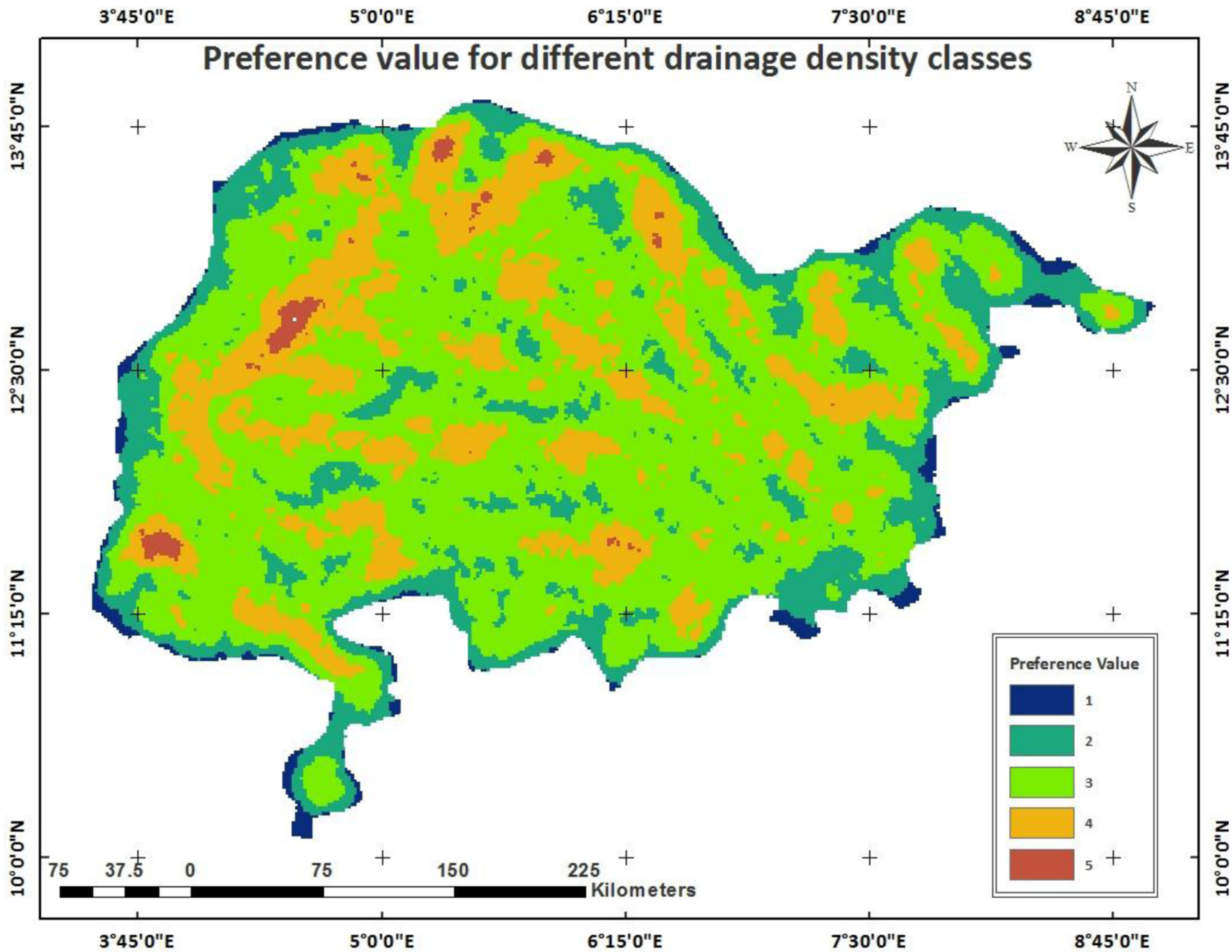

Fig. 10. Map showing the spatial distribution of the density classes and their preference values.

proposed sites for water storage structures. The capacity of the water storage structures were generated with the DEM and the outlet elevation using Watershed Modeling System (WMS).

The relationship between elevations at various interval below the water storage structure and surface area at the elevation intervals were evaluated to estimate the capacity of the water storage structures using the hydraulic toolbox in the Watershed Modeling System software. Analyzing surface area is an important aspect for analyzing the risk that are associated with the water storage structures. The surface area was generated using 30 m DEM and the outlet elevation in the ArcGIS environment. However, the surface area only gives very simplistic idea of what will occur when stored water reaches the outlet elevation. For more accuracy, a finer resolution DEM would be needed.

2.2.5. Water storage structure break analysis

Analysis of the floodplain below the water storage structures is an important aspect of designing water storages. This boundary extent was chosen in order to visualize what a flood wave would do if the water storage structures were to break and empty the entire storage downstream. Gridded Surface Subsurface Hydrologic Analysis (GSSHA) was used to model the flood plain and it utilizes a 30 m resolution DEM with a 100 m by 100 m computation grid. The water storage structures were specified to drain stored water in their full states in 1 h 30 min. The simulation was set up to run for nine hours to give the flood wave plenty of time to spread in the area.

3. Results and discussion

3.1. Land use/cover

Land use/cover represent human influence of hydrological process of runoff and infiltration. Certain land use/cover types support runoff or while others support infiltration. Land use/cover such as built-up and bare ground support development of high runoff against infiltration (Fagbohun, 2018). The study area was classified into four land use/cover classes (Fig. 3): built-up, agriculture, outcrops and water bodies. The suitability preference of the various land use/cover types is provide in Table 4.

3.2. Lineament

The lineament density map derived for the study area (Fig. 4) was classified into categories related to preferential level of constructing water storage structures. The classes indicate the lineament density in the level of 0–0.000178923 km^2, 0.000178923–0.000357847 km^2, 0.000357847–0.00053677 km^2, 0.00053677–0.000715694 km^2, and 0.000715694–0.000894617 km^2. Table 5 and Fig. 4 show the preference values for different lineament density classes

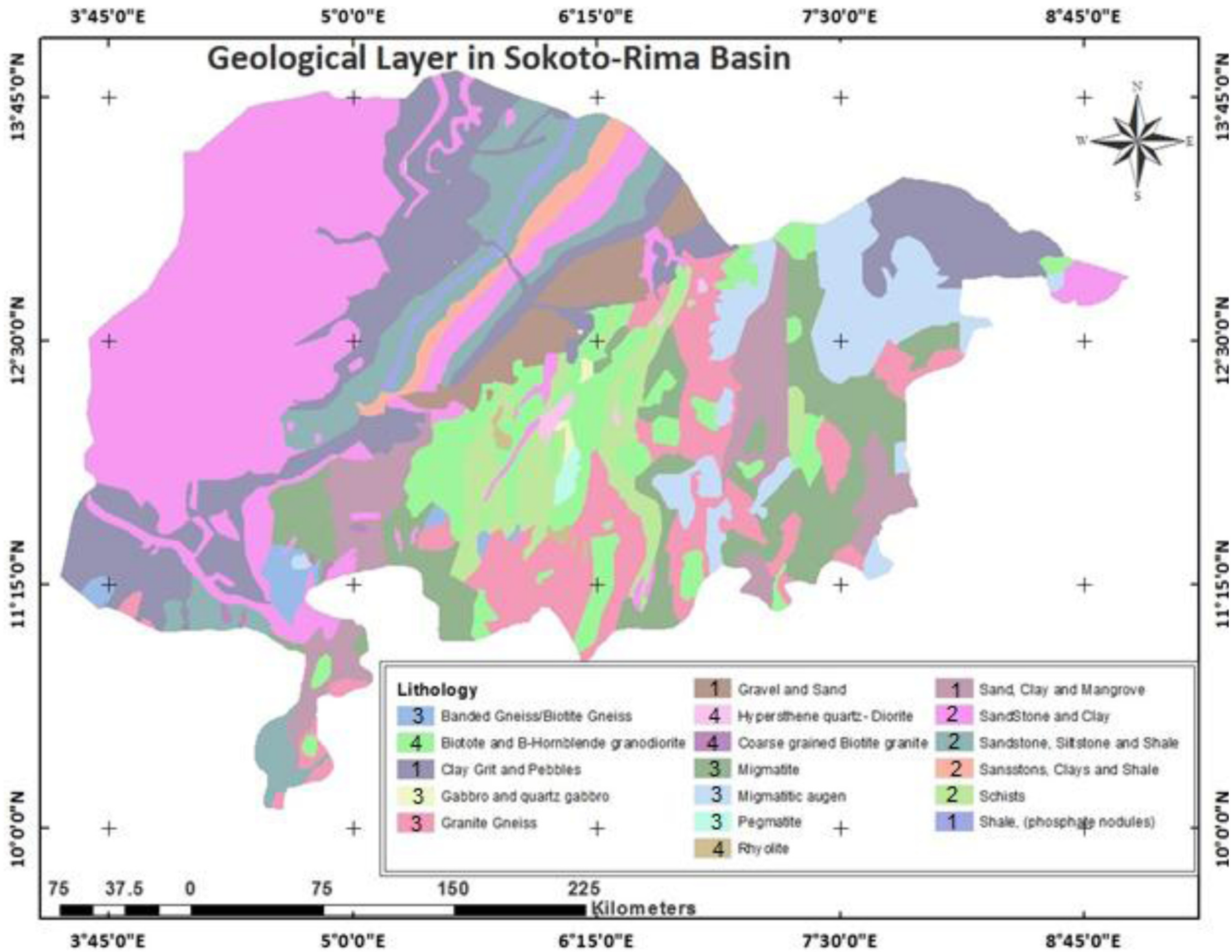

Fig. 11. Map of soil types and assigned preference values.

Table 11
Preference values for rock types in the study area.

Lithology	Modified classification	Preference value	Unified preference
Rhyolite	High Resistance	4	95
Biotite and biotite Hornblende granodiorite			90
Hypersthene quartz-Diorite			85
Granite Gneiss	Moderate Resistance	3	75
Banded Gneiss/Biotite Gneiss			70
Migmatite			68
Migmatitic augen			65
Gabbro and quartz gabbro and meta intrusive			62
Pegmatite			54
Sandstone, Siltstone and Shale	Slightly Low Resistance	2	48
Schist			45
Sandstone and clay			41
Shale			39
Sand, Clay and Mangrove	Low Resistance	1	25
Gravel and sand			20
Clay grit and pebbles			15

3.3. *Slope*

Slope is one of the important factors for deciding the location of water storage structure. It also influences the amount of rainfall that either infiltrates or runs off. Siting water storage structures on a very steep terrain will eventually lead to structural failure. Therefor water storage structures are sited on level to gentle slope. For water storage structures, different slope thresholds have been chosen in previous studies such as less than 10% (Singh et al., 2009), less than 3% (Abushandi and Alatawi, 2015). In this study slope is subdivided into 5

Table 12
Pairwise comparison preference matrix.

	Precipitation	Slope	Geological foundation	Lineament density	Soil type	Drainage order	Drainage density	LULC
Precipitation	1	2	3	4	5	6	7	8
Slope	0.5	1	2	3	4	5	6	7
Geological foundation	0.333	0.5	1	2	3	4	5	6
Lineament density	0.25	0.333	0.5	1	2	3	4	5
Soil type	0.2	0.25	0.333	0.5	1	2	3	4
Drainage order	0.167	0.2	0.25	0.333	0.5	1	2	3
Drainage density	0.143	0.167	0.2	0.25	0.333	0.5	1	2
LULC	0.125	0.142	0.167	0.2	0.25	0.333	0.5 S	1

Table 13
Values for random index (Saaty, 1977).

Number of factor	2	3	4	5	6	7	8
Random Index	0	0.52	0.9	1.12	1.24	1.32	1.41

classes; high slope, moderate to high slope, moderate slope, gentle slope and level to gentle slope as shown in Fig. 5 and Table 6.

3.4. Precipitation

The predicted average annual precipitation for 2041–2060 varies from 39.1667 mm to 98.25 mm. Rainfall pattern of Sokoto-Rima River Basin showed decreasing trend towards the northeast. Highest rainfall amounts are concentrated in the southeast. A classification was carried out to classify the values into classes related to preferential level of constructing water storage structures. Table 7 and Fig. 6 show the various classes and their preferential values for water storage suitability

3.5. Soil

One of the most important features of soil, from the standpoint of its water holding capacity is variation in porosity with depth. Porosity is a measure of the open space between soil particles. There are five classes of soil in this region. According to the different percentage components

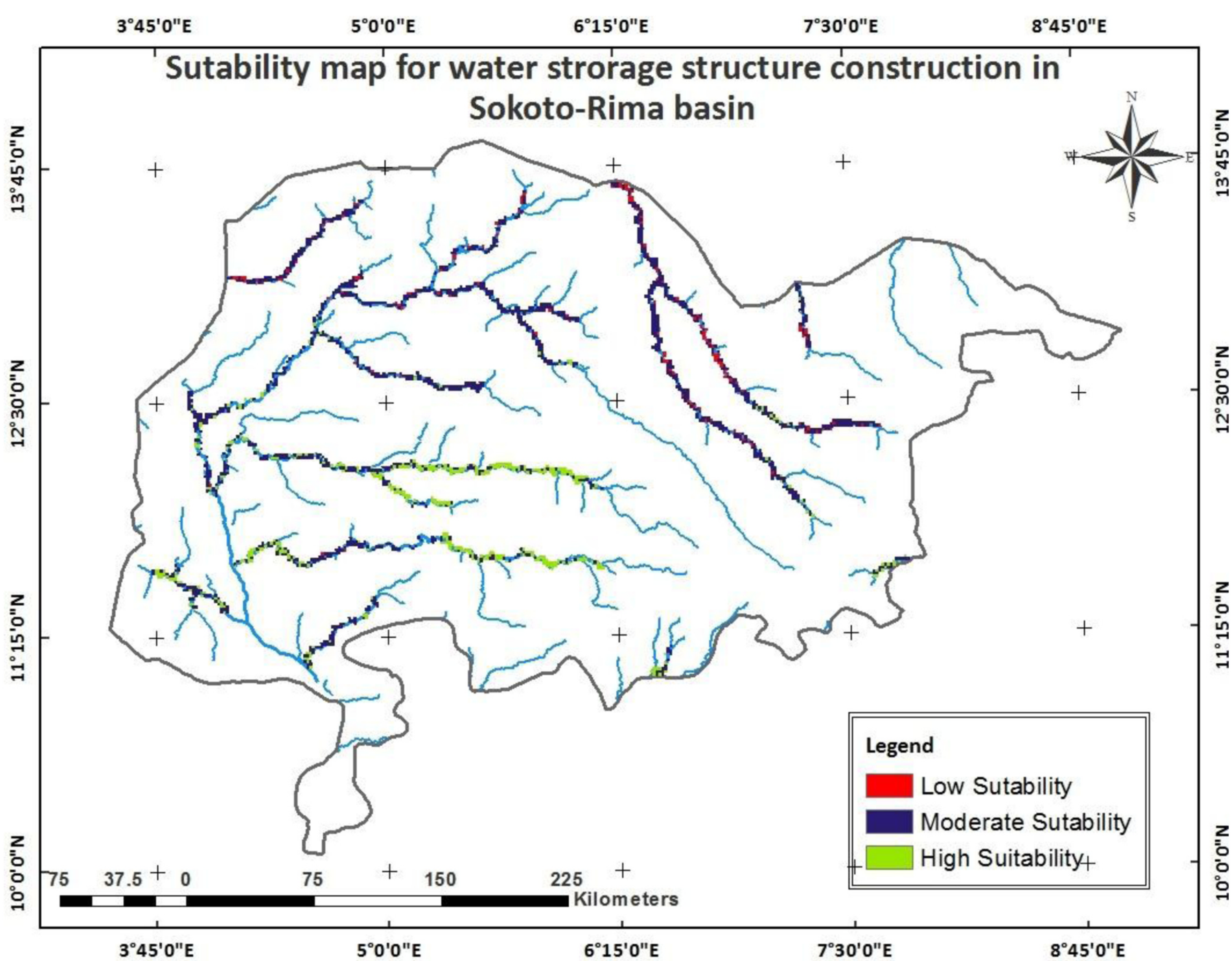

Fig. 12. Suitability map for constructing water storage structures.

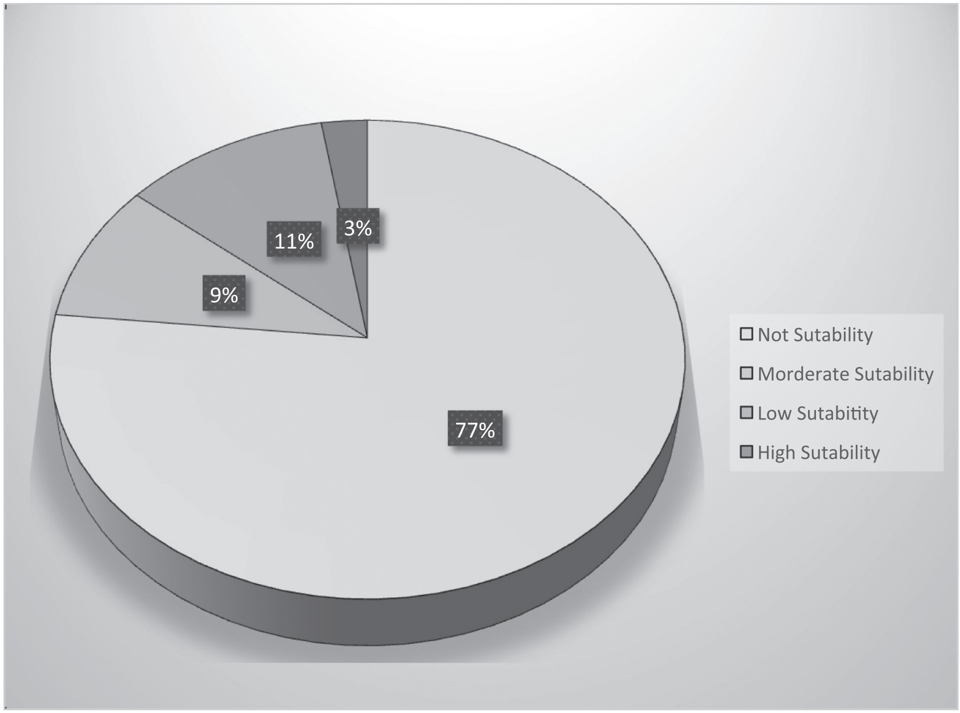

Fig. 13. Percentage of different suitability levels of Sokoto-Rima basin.

Table 14
Classification of weighted factors for site suitability analysis.

Factors	Classes	Unified preference value	Factor weight
Precipitation (mm)	39.1667–50.983	20	27.7%
	50.983–62.800	40	
	62.800–74.617	60	
	74.617–86.433	80	
	86.433–98.25	95	
Slope	0–1	95	24.0%
	1.001–2	80	
	2.001–3	60	
	3.001–4	40	
	4.001–5	20	
	5.001–72.609	0	
Lithology	Rhyolite	95	18.4%
	Biotite & biotite Hornblende granodiorite	90	
	Hypersthene quartz-Diorite	85	
	Granite Gneiss	75	
	Banded Gneiss/Biotite Gneiss	70	
	Migmatite	72	
	Migmatitic augen	65	
	Gabbro and quartz gabbro and meta intrusive	62	
	Pegmatite	54	
	Schist	48	
	Sandstone, Siltstone	45	
	Sandstone & Clay	41	
	Shale	39	
	Sand clay & mangrove	25	
	Gravel & Sand	20	
	Clay Grit & pebble	15	
Lineament density	**0–0.000178923**	**95**	**12.8%**
	0.000179–0.000358	75	
	0.000358–0.00054	50	
	0.00054–0.000716	25	
	0.000716–0.000895	5	
Landuse/Land cover	Water Body	50	8.2%
	Built-up	0	
	Rock outcrop	0	
	Farmland	95	
Soil	Sand	20	4.9%
	Loamy sand	40	
	Sandy loam	60	
	Loam	80	
	Sand clay loam	95	
Drainage order	1	20	2.7%
	2	40	
	3	60	
	4	80	
	5	95	
Drainage density	0–0.000179	20	1.3%
	0.0001789–0.000358	40	
	0.000358–0.00054	60	
	0.000537–0.0007157	80	
	0.0007157–0.0008947	95	

of each soil type, a simplified classification was done to infer the infiltration capacity of different soil types in study area.

Textural triangle describes the relative proportions of sand, silt and clay in various types of soils as well as their infiltration rates. According to the basic infiltration rates of each type of soil (Brouwer et al., 1990), the preference values for constructing water storage structures are assigned to soil types, which shown in Table 8 and Fig. 7.

3.6. Drainage network

Drainage networks can also be referred to as river network represents areas of land where all surface water converges and to be further transported to other locations through fluvial process. For selecting location for constructing of water storage structures, it is necessary to have drainage networks extracted. Then, drainage order was

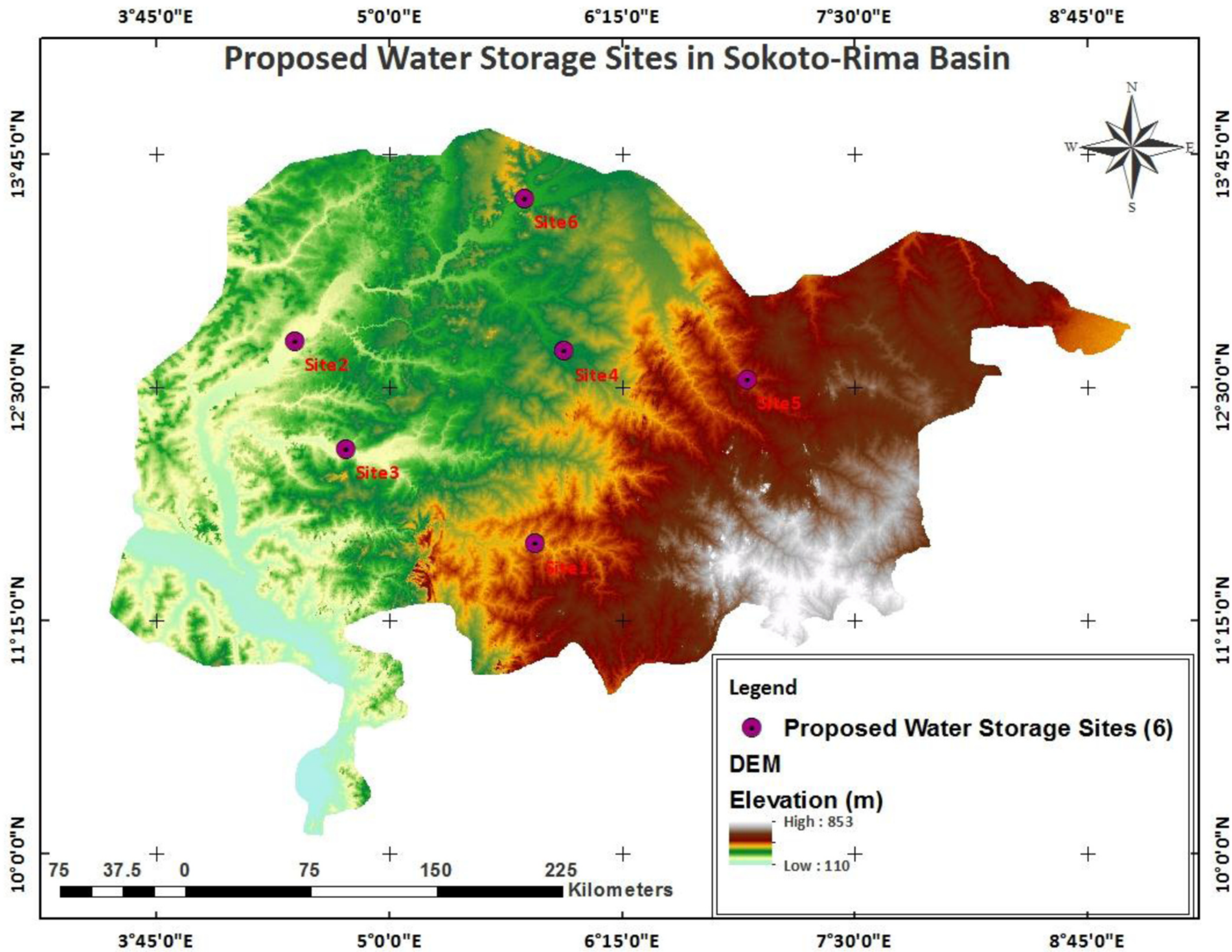

Fig. 14. Proposed water storage structure sites.

assigned to each section of streams. The greater the flow accumulation of a stream, the higher the drainage order assigned to this stream. In another words, higher drainage order indicates more tributaries are flowing into the river which gives a higher possibility to harvest more water. Drainages in the area were ordered (Fig. 8) using the Strahler (1957) method. Buffer was created around the rivers (Fig. 9) in order to constrain suitable sites to areas either along or immediate neighborhood of the rivers. The preference values of the various distances from rivers is provided in Table 9 and Fig. 9.

3.7. Drainage density

Drainage density was calculated as the ratio between total length of the streams in the basin and total area of basin. Areas with higher values of drainage density indicate that those areas have high amount runoff. Drainage density value of study area ranges between 0 and 0.00054 m/km^2. Preference values for drainage density classes are presented in Table 10 and Fig. 10.

3.8. Lithology

Lithological factor is one of the most important factors that affects water storage construction. In a summary of water storage structure performance statistic, most shared causes of water storage failure were found out to be problem emanating from base fabric (Wyllie, 2003). Competent rock foundations have high resistance to erosion, percolation and pressure (US Army Corps of Engineers, 2005). According to the characteristics of different rock types present in the study area (Fig. 11), preference values were assigned based on their perceived stability to support water storage structure inferred from their origin, mineral composition and geologic history. The preference values assigned to the rocks in the study area is given in Table 11.

The weight for each factor was derived using AHP through pairwise comparison of the factors. The weights for the factors considered in the site suitability analysis is given in Table 12.

3.9. Evaluation of matrix consistency

Pairwise comparison value depends on subjective verdict which might lead to arbitrary result with unfair preference. Hence, an evaluation is needed. Consistency Ratio (CR) is a numerical index used for evaluating the consistency of pairwise comparison matrix following the proposal in AHP (Saaty, 1977). This index indicates the ratio of the Consistency Index (CI) to the average consistency index, which also called Random Index (RI), as shown in Eq. (2).

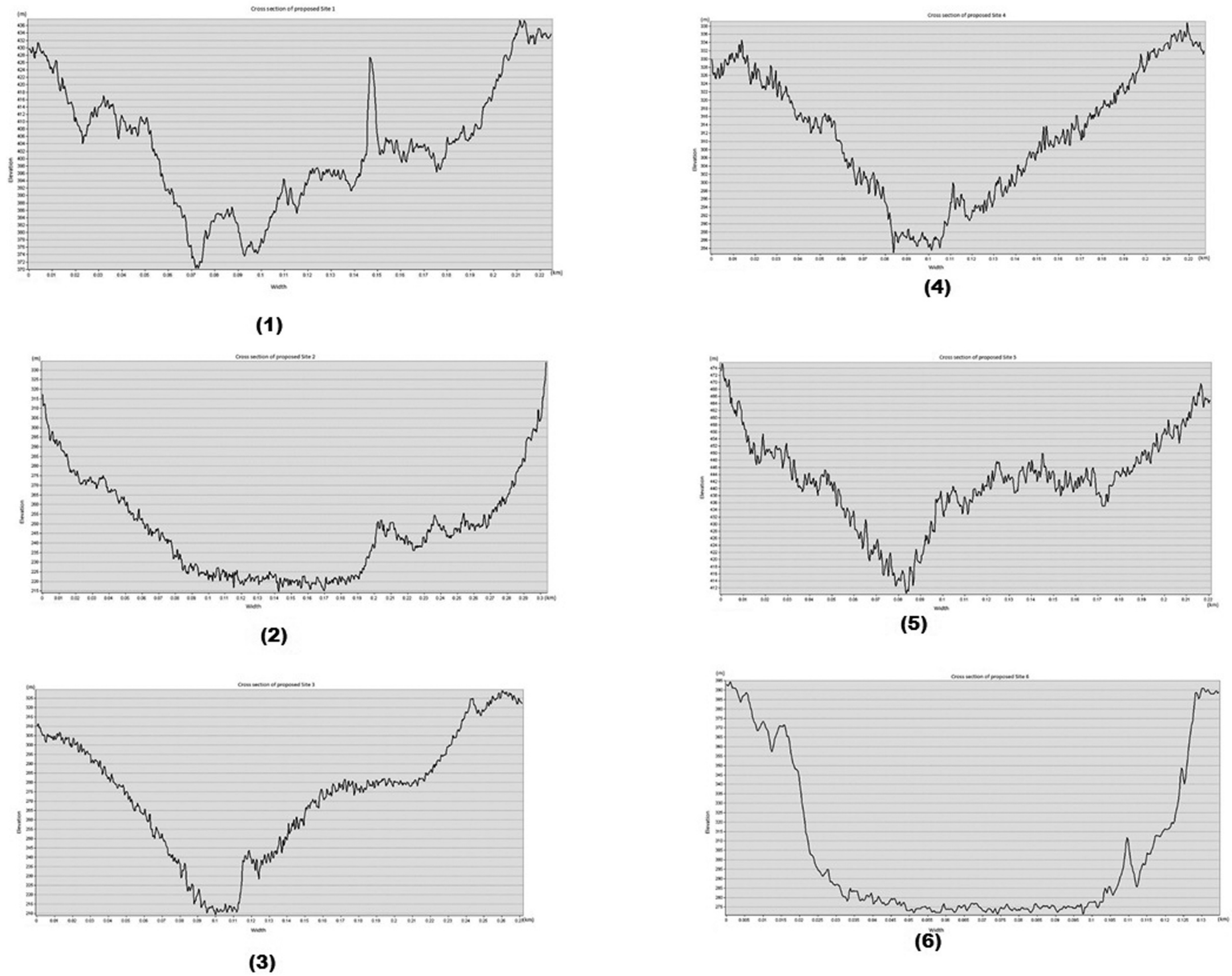

Fig. 15. Cross section of proposed Site 1–6.

$$CR = \frac{CI}{RI} \tag{2}$$

The value of RI can be found in a Table 13, according to number of criteria involved

The Value of CI can be calculated from the preference matrix according to Eq. (3).

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3}$$

Where λ_{max} shows the greatest eigenvalue of preference matrix and n is number of criteria involved.

The value of Consistency Ratio was compared to the maximum CR value (0.1) for an acceptable pairwise comparison (Saaty, 1977). The CR value of Table 12 is 0.0621 which is less than the acceptable maximum Consistency ratio value recommended by Saaty (1997).

3.10. Identification of proposed water storage structures site

Remote sensing and GIS enable utilization of available geospatial data and technology for choosing suitable site for water storage structures. Suitability map for constructing water storage structures in Sokoto-Rima basin is shown in Fig. 12 and pie chart showing percentage of suitability level is shown in Fig. 13.

A multi-layer combination of predicted precipitation, LULC, slope, lithological layer, lineament density, soil types, distance to stream and drainage density based on Table 14 was used to produce suitability site for water storage structures. In general, 3% (131.89 km^2) area of Sokoto-Rima basin is considered to be highly suitable, 9% (486.19 km^2) of the basin area is moderately suitable, 11% (596.05 km^2) of the basin area have low stability for siting water storage structures and 77% (3967.62 km^2) of the basin is not suitable.

Variation in the resolution between datasets caused considerable uncertainty and reduces the accuracy of the suitability map. Another origin of uncertainty is the subjective verdict on weight assigned to different factor. The verdict on the weight assigned to each factor were

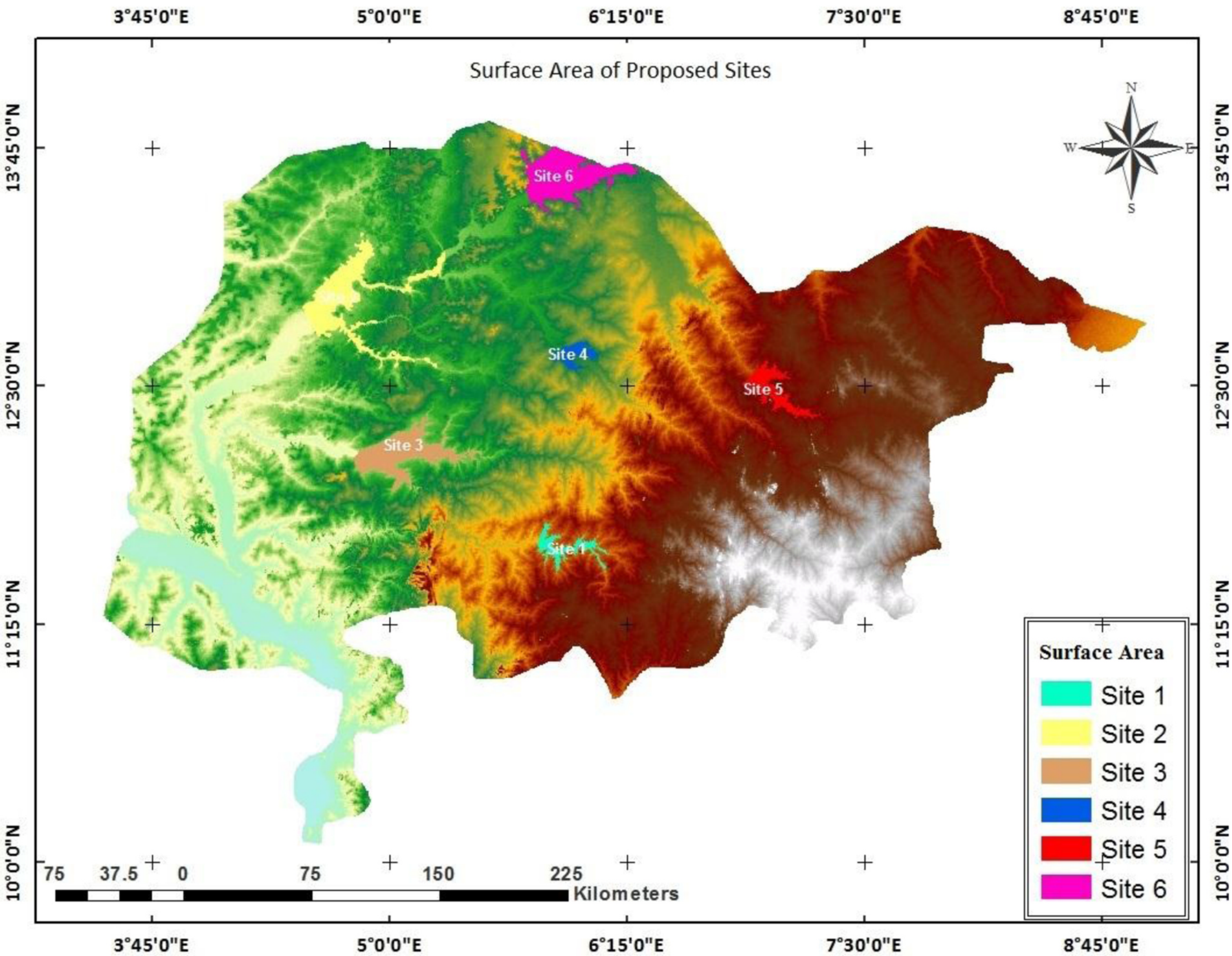

Fig. 16. Water storage area for proposed sites.

based on previous studies.

3.11. Proposed water storage sites

After identification of suitable sites using in the entire study AHP, the potential sites were narrowed down by combining drainage network, suitability layer, cross-section graph generated from digital elevation model and triangulated Irregular Network (TIN). Six potential locations for water storage structures were subsequently proposed. The location of proposed suites for water storage structures is shown in Fig. 14.

A subjective verdict on lowest possible distance between two potential water storage structure sites has implemented during suitable site selection. It is required to maximize the distance between two potential water storage sites to avoid redundancy.

3.12. Profile of potential sites for water storage structures

To get the profile for every proposed location for water storage structure, contour layer (5 m interval) was generated from DEM. Triangulated Irregular Network (TIN) and 5 m interval contour line layer was used for drawing interpolation line, which is necessary to obtain cross section profile, and calculating the capacity of water storage structures. The cross section and storage area of the six potential sites for water storage structure is shown in Figs. 15 and 16.

Additionally, the analysis of possible hazard from extents of flood (Fig. 17) proved to be catastrophic to the farmlands in the area and would place an immense economic strain on the surrounding areas with a long lasting impact. However, it is important to note that simulation is conservative by nature.

Fig. 17 shows the extent of flood in various suitable location for constructing water storage structure. The simulation of the event shows that the event of the storage walls washes out in an instant and all the content of the storage are released downstream. In reality, most water storage structure failures have a much slower release and failure rate than the simulations.

The defining features of the potential site for water storage structures are shown in Table 15.

4. Conclusion

Reacting to scarcity of water in the dry season and occurrence flash flood in the raining season water storage structures are needed in the northwestern part of Nigeria. Water storage structures provide a host of hydrologic, social, environmental and economic benefit. In this study, a suitability map for constructing water storage structure, cross section, surface area and capacity of six potential water storage structure sites were generated for Sokoto-Rima basin. Due to the complexity of water storage structure site selection, Analytic Hierarchy Process which is a Multi-Criteria Decision Making method was used in this study. Analytic Hierarchy Process provides an integrated measurement on important factors with different priority by pairwise comparison. Geographic Information System (GIS) (Arc GIS 10.5) was used for implementation of Analytic Hierarchy Process through integration of factors based on

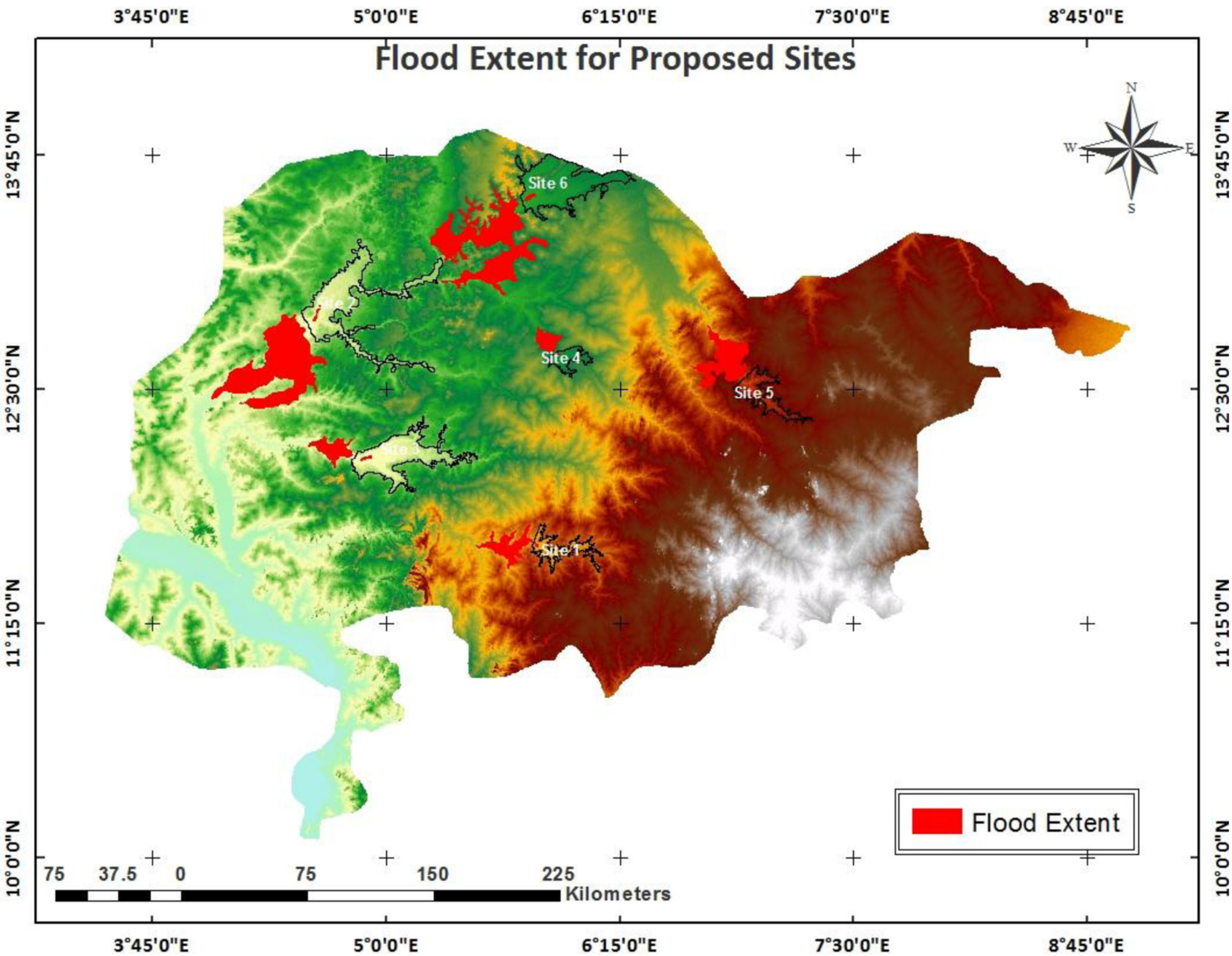

Fig. 17. Flood extent of proposed sites for water storage structures.

Table 15
Defining features of the potential site for water storage structures.

Proposed site	Longitude (E)	Latitude (N)	Base elevation (m)	Outlet elevation (m)	Surface area (m^2)	Storage capacity (m^3)	Flood extent (m^2)
Site 1	5°46′28.76″	11°39′29.81″	370	400	38,370	5,010,000	282,200,193
Site 2	4°29′22.45″	12°45′6.48″	215	250	1,662,754	27,450,000	1,553,769,949
Site 3	4°45′35.71″	12°10′57.91″	210	250	32,403	4,850,000	213,548,661
Site 4	5°56′0.76″	12°41.45.94″	283	300	87,572	14,250,000	131,525,463
Site 5	6°54′55.78	12°33′9.76″	411	450	72,523	13,450,000	513,324,676
Site 6	5°43′13.37″	13°30′45.11″	272	300	1,144,385,910	30,500,000	1,476,798,983

weight derived through pairwise comparison to generate suitability map for water storage structures as well as presentation and visualization result obtained.

Furthermore, six potential sites for water storage structures were proposed based on the information gotten from the suitability map. The six proposed sites for water storage structures are located in highly suitable region of the study area. Along with the location of potential sites for water storage structures, cross section of the sites was generated, surface area, flood extent and capacity of the proposed sites were estimated. The results of this study can be useful for environmental planners for planning future locations of water storage structures which will be of agricultural, environmental, economic and societal benefit to the study area.

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